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Sea-level control of gravity-flow deposits in the Middle Ordovician in Pingliang, North China

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Abstract

The Middle Ordovician strata in Pingliang of Gansu Province, western North China, consist of a series of gravity-flow carbonates and fine-grained sediments. The deposits in the Pingliang Formation are organized into seven lithofacies as well as five lithofacies associations, which were deposited from outer ramp to basin plain environments.

The Pingliang Formation is dominated by short-term fining-upward lithofacies sequences, illustrated by coarse, thick carbonate conglomerates and/or packstone/grainstone grading upward into fine-grained carbonates or shale. The coarsening-upward lithofacies sequences, only a few in the Pingliang Formation, consist of lower fine-grained deposits and upper turbidite/debrite-dominated lithofacies. The short-term lithofacies sequences in the formation are superimposed on long-term successions, including five retrograding and one prograding lithofacies sequences. The entire Pingliang Formation was deposited as a retrograding succession as shown by the vertical succession of the short- and long-term lithofacies sequences.

The deposition of the Pingliang Formation shows synchronous changes of the stacking patterns of lithofacies associations with that of the coeval Fengfeng Formation on the shallow-water carbonate platform of eastern North China. Debrite-rich intervals in the lower part of the Pingliang Formation are correlatable with the lowstands deposits characterized by solution collapse breccia/argillaceous dolostone of the Fengfeng Formation, suggesting that the former might also have been deposited mainly during lowstands of sea level. In contrast, terrigenous muds dominated the sedimentation of the Pingliang Formation in the basin during sea-level highstands, while coeval subtidal lithofacies associations prevailed in eastern North China. Six long-term lithofacies sequences of the Pingliang Formation can also be correlated with the long-term, shallowing-upward cycles in the Fengfeng Formation, deposited on the carbonate platform.

This study indicates that the development of the gravity-flow deposits in the Pingliang Formation in Pingliang was largely controlled by sea-level fluctuation rather than by autocyclic factors or by local tectonic activity.

Key words: Gravity-flow sediments, Sea-level changes, Middle Ordovician, Pingliang.

Introduction

The Middle Ordovician strata in North China have two main lithofacies types. Shallow-marine carbonates prevailed on the interior of the Sino-Korean Massif, and slope-and-basin deposits are present especially along the southern and western margins of the massif. This marginal area is named as the "Western paleogeographic province", in contrast to the interior of the Sino-Korean Massif (An, 1986)

In Pingliang, the Middle Ordovician strata have been termed the "Pingliang Shale" since the 1920's, and have long been treated as the typical stratigraphic section in the Western paleogeographic province. The geologic studies of the Pingliang Formation in the area have been concentrated mainly on the biostratigraphy (Chen et al., 1984; An and Zheng, 1990), whereas sedimentological studies were neglected.

After detailed field observation and study of section logs, we have distinguished a large amount of carbonate conglomerate layers as well as packstone/grainstone in the Pingliang

Formation, which are interbedded with shale and lime mudstone. The vertical succession of the lithofacies associations in the Pingliang Formation shows a regular evolutionary history, implying that some non-random forcing factor, e.g., tectonic or sea-level change, may have controlled the development of the deposition of the formation.

The purposes of this paper are: (1) to describe the lithofacies and lithofacies associations; (2) to distinguish the stacking patterns of the lithofacies associations; and (3) to discuss the controlling mechanisms on the deposition of the Pingliang Formation.

Geological settings and biostratigraphy

The studied area is located in the southwestern margin of the Sino-Korean Massif (Fig. 1). The Ordovician strata here were deposited conformably on the Cambrian strata and were overlain unconformably by the Permian (Fig. 2). The Lower Ordovician deposition in Pingliang and adjacent areas comprise shallow-marine car-

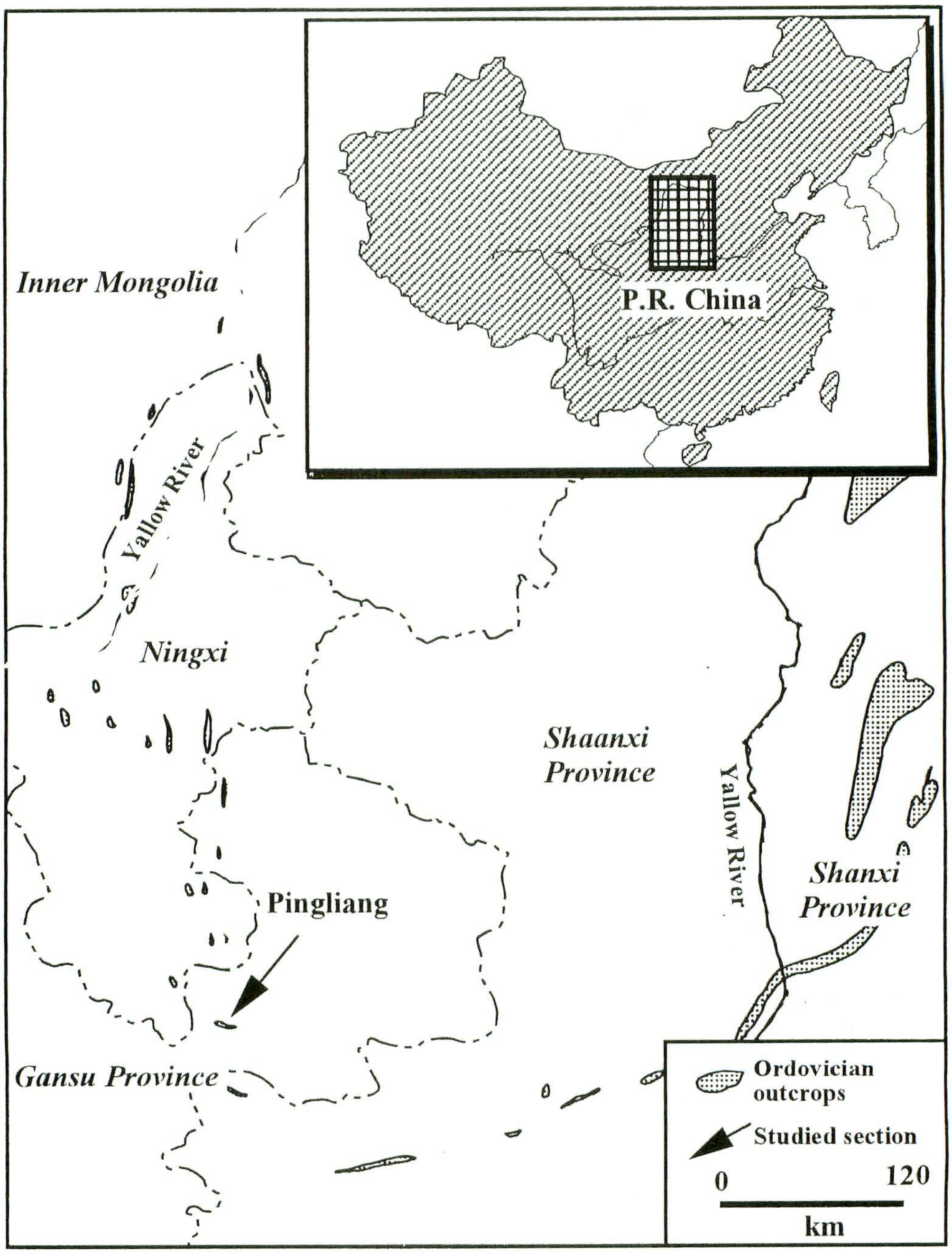

Fig. 1. Outcrop map for the Ordovician in the western and southern margins of the Sino-Korean Massif. Locality of Pingliang in Gansu Province, North China is indicated by arrow.

bonates, interrupted by several unconformities. From the beginning of the Middle Ordovician, the shallow-marine carbonates were overlain by deep-water sediments in the southern and western margins of the Sino-Korean Massif. However, in the massif's interior, the deposition of the Middle Ordovician was still dominated by shallow-marine carbonates.

Two outcrops were selected from Pingliang for this study. The Pingliang Formation is well exposed at Yindongguanzhuang village, 8 kilometers southwest of Pingliang county (Fig. 2). However, the Yindongguanzhuang section lacks the lowermost part and lower boundary of the formation. Thus, another section was selected from the Sandaogou section in order to supply the missing horizon of the Pingliang Formation. The Sandaogou section is about 15 kilometers southeast of Pingliang (Fig. 2), and the boundary between the Pingliang Formation and the underlying Sandaogou Formation is clearly exposed here. The top of the Sandaogou section should be near the base of the Yindongguanzhuang section, though the direct correlation between the two sections remains uncertain.

The biostratigraphic scheme of the Pingliang Formation at Pingliang is clearly defined by the studies on graptolite and conodont biozones (Table 1). According to the correlation with biozones established in Britain, Baltoscandia and North China, the Pingliang Formation ranges from the lower Llandeilian to the Caradocian of the Middle Ordovician, and it can be correlated, approximately, with the Fengfeng Formation, the shallow-marine carbonates in eastern North China (Table 2).

Lithofacies

The Pingliang Formation in Pingliang consists of various lithofacies, distinguished from each other using the data of field observations and descriptions of thin sections. The lithofacies of the Pingliang Formation include autochtho-

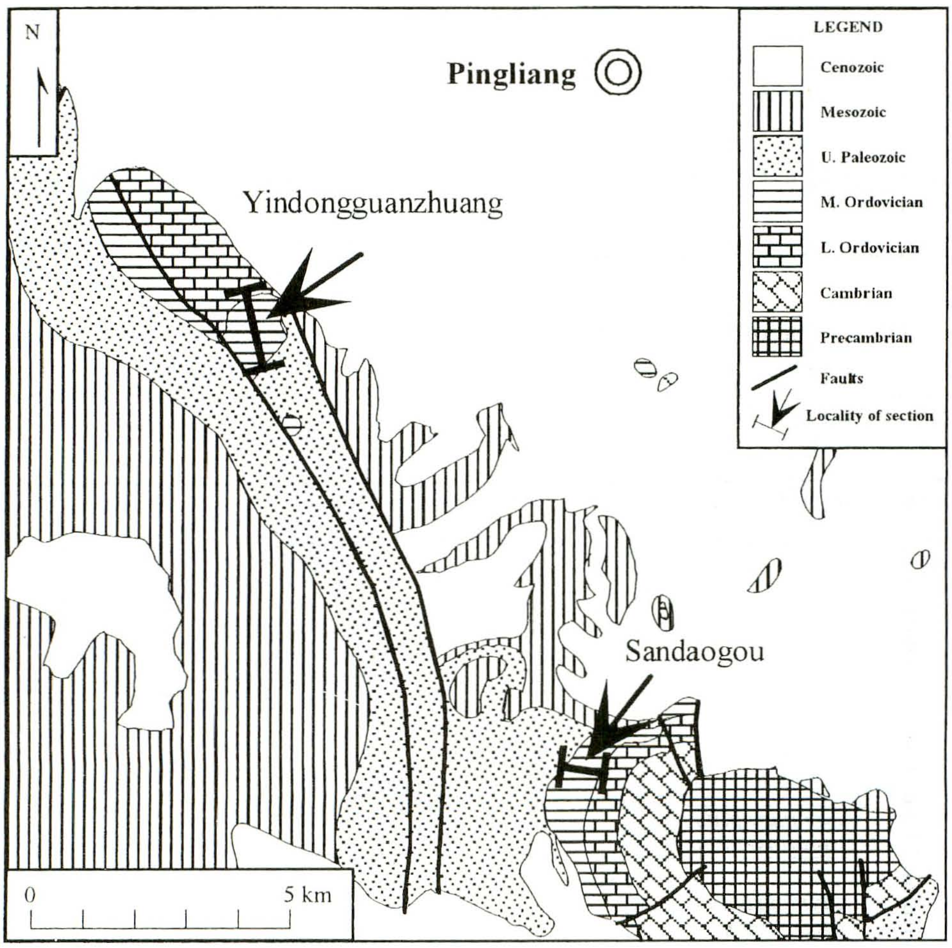

Fig. 2. Simplified geological map of the area around the studied sections in Pingliang County, Gansu Province. Two studied sections are indicated by arrows.

nous carbonates (nodular argillaceous lime mudstone, bioturbated lime mudstone, thin-bedded lime mudstone), allochthonous carbonates (conglomerate, packstone, grainstone), fine-grained clastics (shale), and volcanic sediments. The volcanic deposits in the Pingliang Formation include bentonite and bentonitic siltstone/sandstone (Fig. 5-C), which will not be described in detail below.

Table 1. Graptolite biozones and conodont biozones in the Pingliang Formation, Pingliang.

Epoch	Stage	Formation	Biozones: Graptolite (Chen et al.,1984)		Biozones: Conodont (An and Zheng,1990)
Permian					
Middle Ordovician	Caradoc	Pingliang Formation	*Nemagraptus gracilis*	*Climacograptus bicornis*	*Tasmanognathus sishuiensis-Erismodus typus*
				Syndyograptus	*Pygodus anserinus*
	Llandeilo		*Glyptograptus teretiusculus*		*Pygodus serrus*

Bioturbated lime mudstone (Fig. 3-A)

Description: This dark-gray lime mudstone is in beds, 4-15 cm thick. Burrowing is generally weak, indicated by grayish green, isolated burrows on a fresh surface. Peloids and articulated brachiopods may appear, but are generally less than 5 percent. Terrigenous muds are occasionally abundant. The lithofacies is commonly interbedded with rare, nodular argillaceous lime mudstone, which only appear near the bottom of the Pingliang Formation.

Interpretation: Development of bioturbation implies that this lithofacies was deposited on a well-oxygenated sea floor (Wilson, 1975; Ross et al., 1989). Micritic matrix and lack of shallow-marine, thick-shelled bioclastics suggest that this lithofacies was deposited on a low-energy outer-ramp, below a fair-weather wave base.

Nodular argillaceous lime mudstone(Figs. 3-A, B)

Description: This lithofacies is commonly medium to dark gray and less than 10 cm in bed thickness. The beds are discontinuous, nodular, wavy. The matrix is dominated by micrite as well as by terrigenous muds, and bioclastics

Table 2. The correlation scheme of the Pingliang Formation, with chronological and biostratigraphic divisions on local and global scales. Absolute age, in million years, after Harland et al. (1989). The graptolite biozones in Britain after Williams et al. (1972) and Fortey et al. (1995); conodont biozones from Baltoscandia after Lindström (1971) and Bergström (1977); conodont assemblage-zones of the Ordovician from North China and Pingliang after An and Zheng (1990).

Time Scale (Ma)	Epoch & Stage		Graptolite biozones: Britain	Conodont biozones: Baltoscandia	Conodont biozones: North China	Strata in North China: Interior	Strata in North China: Pingliang
460	Middle Ordovician	Caradocian	*Climacograptus peltifer*	*Amorphognathus tvaerensis*	*Tasmanognathus sishuiensis-Erismodus typus*	Fengfeng Formation: Badou Member	Hiatus
			Nemagraptus gracilis				Pingliang Formation
		Llandeilian		*Pygodus anserinus*	*Scandodus handanensis*	Fengfeng Formation: Gezhuang Member	
			Glypotograptus teretiusculus				
	L.Ordovician	Llanvirnian	*Didymograptus murchisoni*	*Pygodus serrus*	*Aurilobudus serratus*	Shangmajiagou Formation	Sandaogou Formation
470					*Plectodina onychodonta*		
				Eoplacognathus suecicus			

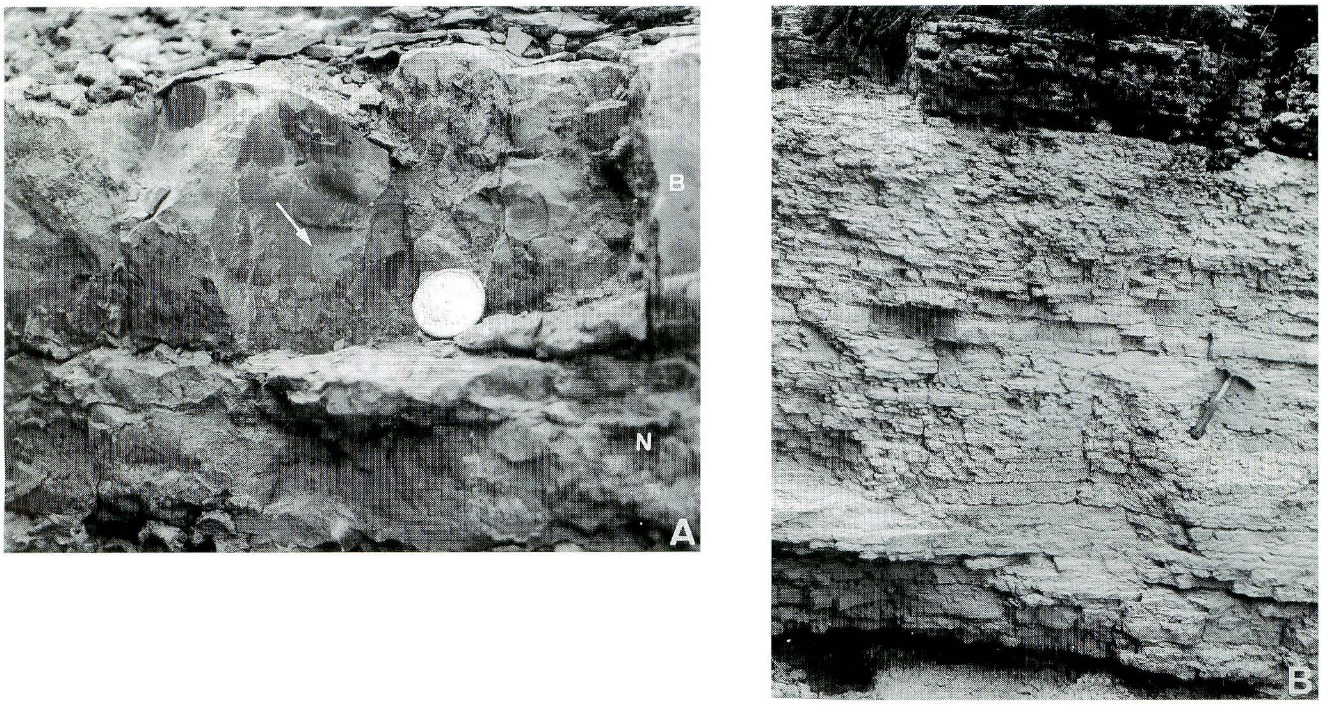

Fig. 3. Outcrop views of autochthonous carbonate lithofacies. A-Bioturbated lime mudstone (B) overlying nodular argillaceous lime mudstone (N). Burrows marked by light color (arrow). B-Nodular argillaceous lime mudstone with interbedded, thin-bedded lime mudstone, comprising lithofacies association A_0.

commonly include only thin-shelled fossils (less than 10%). The degree of bioturbation is generally low.

Interpretation: Nodular argillaceous mudstone may be deposited on a ramp, between bioturbated lime mudstone and deeper water siliciclastic muds (Aigner, 1985) or on slope environments (Mullins et al., 1980). Nodules in this lithofacies may have been formed early by submarine lithification under weak bottom currents (Mullins et al., 1980) and enhanced by late pressure solution and physical compaction (Wanlass, 1979).

Clast-supported carbonate conglomerate (Figs. 4-A, B)

Description: The lithofacies has a wide variety of clasts and textures. Individual beds range in thickness from about 0.1 m to as much as 5.8 m. Massive structures are common. Normal grading can be occasionally observed, especially near the base of beds. The lithofacies is clast-supported. The matrix consists of finer grained carbonate clasts and lime/terrigenous mud. Clasts, as large as 40 cm, are commonly sorted, but have no preferred orientation. Based on the shape and the lithologies, two types of clast can be distinguished. Most of carbonate clasts are rounded (Fig. 4-A), yielding exotic conodont fauna. Other carbonate clasts, together with shale clasts, are generally tabular (Fig. 4-B), and have plastic deformation in some instances. The bases of the beds are abrupt, and upper contacts occasionally pass upward into packstone.

Interpretation: Many of the features described above have been recognized in submarine mass flows, where transport was achieved largely by debris flow (Cook and Mullins, 1983; Enos and Moore, 1983; Coniglio and Dix, 1992). Rounded carbonate clasts yielding exotic conodont fauna may be eroded from older stratigraphic intervals, and tabular clasts may be incorporated into rounded clasts from the floor of the slope environment before deposition of conglomerates. Carbonate conglomerates are interpreted as resulting from major collapses in the shelf margin-upper slope region, from erosion of old strata, and from incorporation of semi-solidified, thin-bedded lime mudstone deposited on the floor of the slope. Primary mechanisms which might have generated such collapses include seismic events, tsunamis and storm waves, gravitational collapse of the outer shelf-upper slope, and sea-level lowering (Cook and Mullins, 1983; Crevello

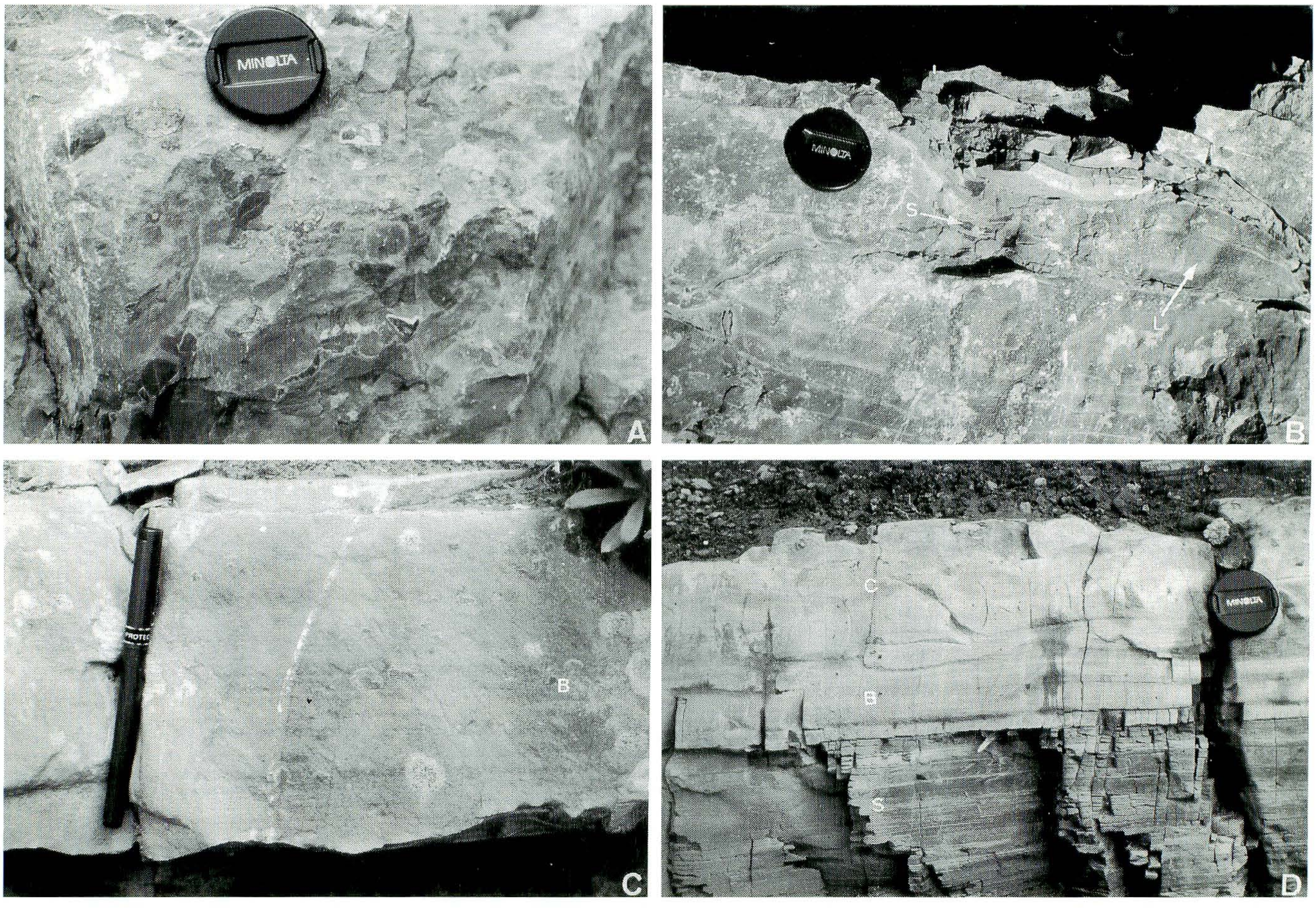

Fig. 4. Outcrop views of gravity-flow sediments. A-Clastic-supported carbonate conglomerate in lithofacies association A. Clasts are commonly well rounded, which are surrounded. B-Clast-supported carbonate conglomerate in lithofacies association A. Clasts consist mainly of tabular lime mudstone (L) and shale (S). C-Packstone with parallel bedding, regarded as Bouma division Tb (B). D-Packstone overlying siliceous shales (S) in lithofacies association C. Packstone consists of lower Bouma division Tb (B)with parallel bedding and upper Bouma division Tc with convolute bedding (C).

and Schlager, 1980). Thus, clast-supported carbonate conglomerates are regarded as debris-flow sediments.

Packstone (Figs. 4-C, D, 6-A)

Description: The bedding thickness of this lithofacies ranges from 2 cm to 58 cm. Clasts are generally well rounded, and micritic, and lack any inner textures. Bioclasts are rare, except robust trilobite fragments and *Girvanella* (Fig. 6-A). Terrigenous muds and rounded quartz sands are occasionally rich. Graded bedding, parallel bedding, and/or convolute bedding/cross bedding are characteristic sedimentary structures for the lithofacies. Size grading is commonly recognized, especially near the bottom of single beds. Submarine slumps may occur (Fig. 5-B). Parallel bedding and convolute bedding, if developed, typically occur in sequences comparable to Bouma divisions (Ta-b, Tb-c, Tc) (Figs. 4-C, D). Beds of this lithofacies either have sharp contacts with underlying shale or gradually decrease in grain size from underlying clast-supported conglomerates. The upper boundaries are usually sharp.

Interpretation: The clasts yielding *Girvanella* are regarded as have been transported from shallow-marine environments, but the other peloids are difficult to be distinguished as exotic particles, due to lack of inner structures. Rounded quartz sands may be transported from surrounding highlands. Thus, this lithofacies is allochthonous. Well-defined Bouma divisions (Ta, Tb, and Tc) indicate that the lithofacies in the Pingliang Formation was deposited by turbidity currents, comparing them with their modern and ancient analogues (Cook, 1983; Mullins, 1983; Coniglio and Dix, 1992).

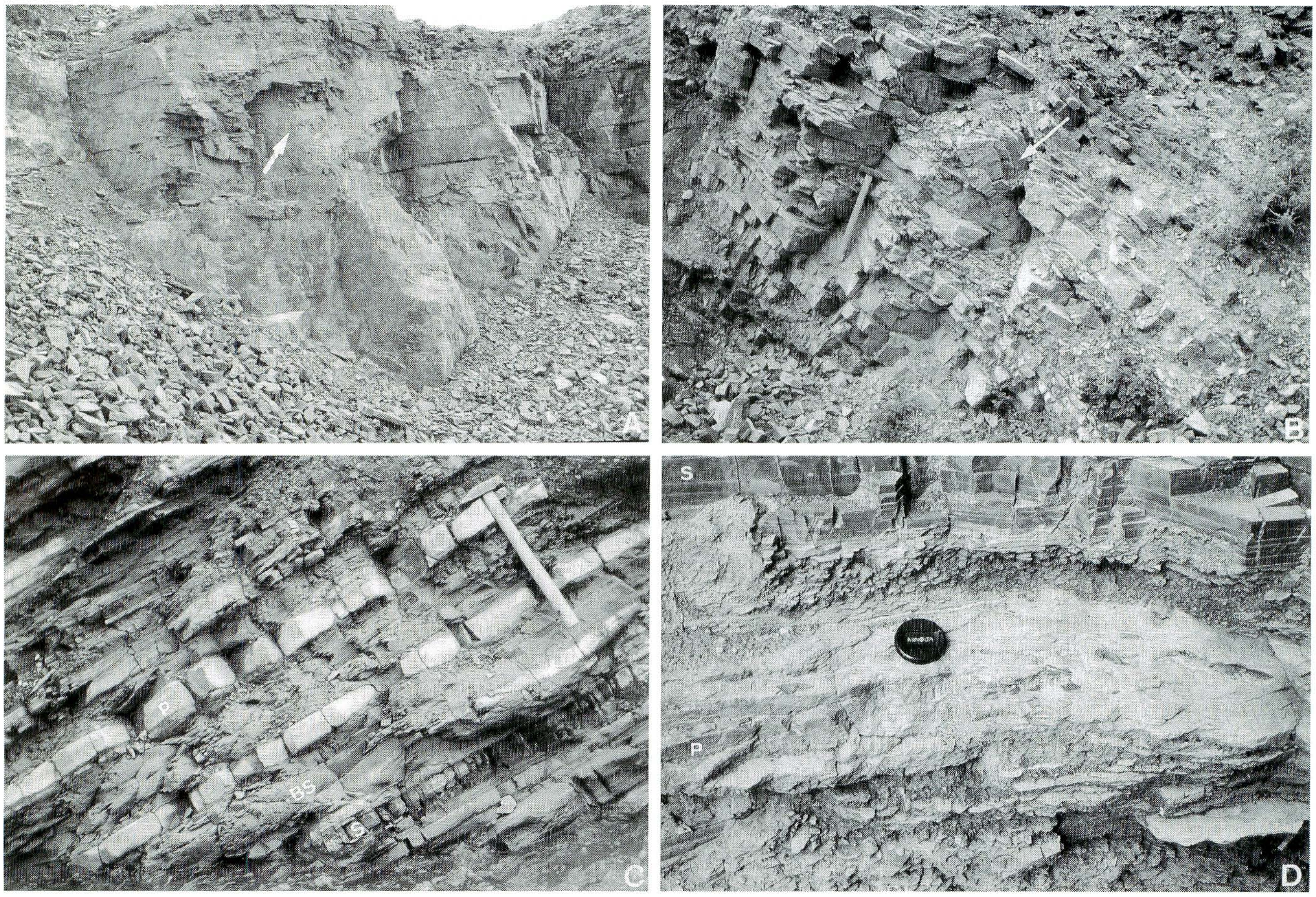

Fig. 5. Outcrop views of various lithofacies. A-Carbonate grainstone with submarine slump (arrow). Its microscope photograph is shown in Fig. 6-B. B-Thin-bedded packstone interbedded with thin-bedded lime mudstone and shale. Slump (arrow) was formed in carbonate apron setting. C-Alternation of green, bentonitic silty sandstone (BS), packstone (P). Siliceous shale (S) is rare. D-Siliceous shale (S) overlying packstone.

Carbonate grainstone (Figs. 5-A, 6-B)

Description: This lithofacies is commonly gray, and medium- to thick-bedded. The lower and upper contacts of the lithofacies are sharp. Clasts are composed mainly of peloids, quartz, and minor robust trilobite fragments; they are well sorted and medium rounded and cemented by sparry calcite (Fig. 6-B). Graded bedding is common in the lithofacies. Slump structures can be observed (Fig. 5-A), but are rare. Grainstone only appears in the upper part of the Pingliang Formation (see Fig. 9), but can be traced along extended outcrops.

Interpretation: Carbonate grainstones are usually proposed as representative deposits of shoal on carbonate platforms (Wilson, 1975). If the grainstone in the Pingliang Formation was, indeed, deposited on a carbonate platform, it collapsed from the platform margin and was deposited as a sedimentary block in deep water sediments. However, there is some evidence against this assumption. Firstly, the lower and upper boundaries of grainstone unit seem to be conformable with both underlying and overlying deep-water sediments. Secondly, thick graded beds and slump structures (Fig. 5-A) seen in the grainstone lithofacies are typical sedimentary structures in slope sediments, and are rather rare in shoal deposits. Hence, the grainstone lithofacies in the Pingliang Formation was not a shallow, shoal deposit. Instead, it was deposited by turbidity currents going by the sedimentary structures and adjacent strata, described above. The matrix-rich turbidites were reworked by bottom currents (contour currents ?). The currents may have been washed the fine-grained matrix away, leaving only the larger clasts to form deep-water grainstone.

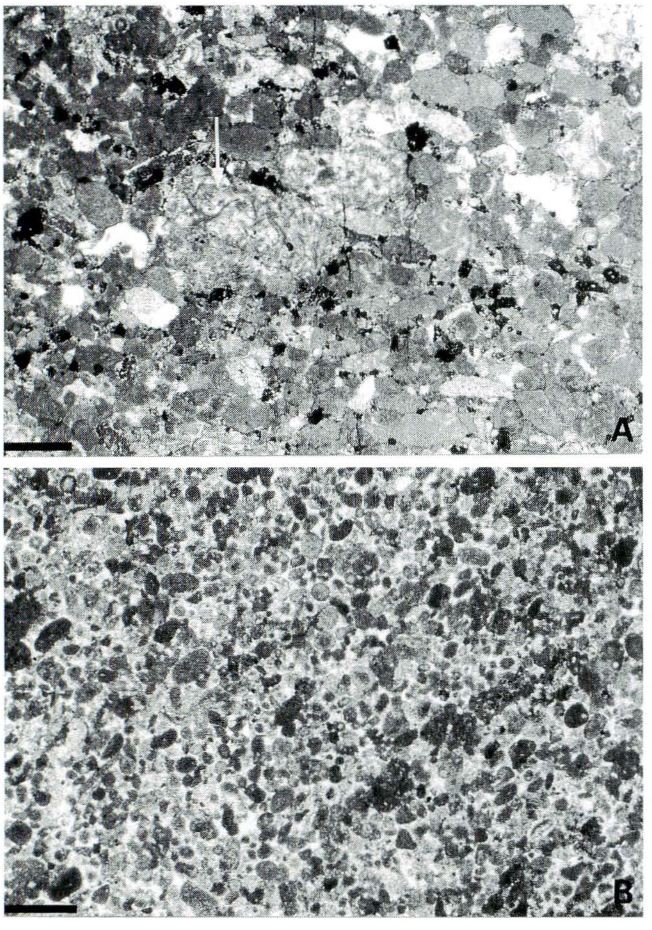

Fig. 6. Photomicrographs of packstone and grainstone. The black bar at the bottom left of the photographs marks 1 mm. A-packstone (cross-view). Clasts include quartz, micritic, algal peloids with *Girvanella* (arrow). B-grainstone with rounded clasts (cross-view). Its field photograph is shown in Fig. 5-A. Note remnants of micritic matrix between clasts.

Thin-bedded lime mudstone (Fig. 5-B)

Description: This lithofacies is commonly gray to dark gray, and 2 cm to 8 cm in bed thickness. Terrigenous muds are generally abundant. Bioclasts are commonly absent, except for occasional radiolarians and spongy spines. Lamination is rare, and is the only sedimentary structure observed in this lithofacies. The lithofacies occasionally grades from lower packstone, but is sharply bounded from the overlying and/or underlying shales.

Interpretation: Thin-bedded lime mudstone within allochthonous successions is generally proposed to have been deposited from either suspension settling or dilute turbidity currents. The origin of the thin-bedded lime mudstone in the Pingliang Formation is rather difficult to document because of lack of sedimentary structures. However, lime mudstones grading from underlying packstone may be distal elements of carbonate turbidite, whereas others with laminites may be deposited in a hemipelagic setting.

Shale (Fig. 5-D)

Description: The shale lithofacies is commonly dark gray to black, and generally silicified. Primary horizontal lamination is well preserved (Fig. 5-D). Fossils in the lithofacies are dominated by abundant, well-preserved graptolite and poorly preserved radiolarians. Bioturbation is absent. The shale intervals range from 0.01 to 2.35 m in thickness.

Interpretation: Well-preserved graptolites suggest that this lithofacies was deposited in a undisturbed, dyaerobic setting (Gawthorpe, 1986). The siliciclastic mud may have been transported by bottom-hugging nepheloid layers (Boardman and Neumann, 1984) or dilute clouds. This lithofacies is the 'background' sediments on Paleozoic slopes when becoming sediment starved (Coniglio and Dix, 1992).

Lithofacies associations

Lithofacies are useful for the description of strata, but they are sometimes difficult for interpretation as they are not unique to any particular environment. However, genetically related lithofacies can be grouped together into preferred associations and are then interpreted in terms of their depositional environments, inferred from their modern analogues and ancient examples. The lithofacies in the Pingliang Formation are grouped into five lithofacies associations, considered as groups of lithofacies occurring together in vertical succession, with genetic and environmental relationships.

Lithofacies association A_0 (Figs. 3-B, 8)

This lithofacies association is characterized by interbeds of nodular argillaceous lime mudstone with minor bioturbated lime mudstone and thin-bedded lime mudstone. Bedding is on a centimeter scale in thickness. Thin-shelled bioclastics, different from robust ones in shallow-marine settings, are the main type of bioclastics in the lithofacies, but comprise less than 5 percent. This lithofacies association is generally free from gravity-flow sediments.

The lack of gravity-flow deposits in this lithofacies association suggests that depositional slopes were gentle. Fine-grained carbonate muds were derived from the platform by storms. Burrows in the lime mudstone indicate that bottom conditions were, at least occasionally, aerobic. This association was deposited in outer ramp environments.

Lithofacies association A (Figs. 4-B, 5-A, 8)

Lithofacies association A consists of carbonate conglomerates and thick, packstone lithofacies, with Bouma division Ta. Shale and thin-bedded lime mudstone lithofacies are rare. The clast-supported carbonate conglomerates, with a polymictic nature, occasionally grade upward into packstone lithofacies with graded bedding.

Various types of allochthonous clasts in carbonate conglomerates suggest a complex source involving a combination of carbonate platform, slope, as well as even different stratigraphic intervals. Debris-flow and turbidite deposits occur as thick sheets, which indicates the development of depositional slopes and associated sediment instability in inner apron settings in terms of Mullins and Cook (1986).

Lithofacies association B (Figs. 5-B, 8)

This lithofacies association consists mainly of packstone and/or grainstone lithofacies and fine-grained lithofacies. Carbonate conglomerates may also occur in the lower part of the association. Carbonate packstone with Bouma Ta divisions grades conspicuously upward into thinner, finer grained, Tb-c distal turbidites.

The lithofacies association B was deposited on the outer apron, similar to its modern analogues, consisting of turbidites with Bouma Ta divisions and interbedded base-cut-out (Tb-c, Tc-d) turbidites, as well as fine-grained sediments (Mullins and Cook, 1986).

Lithofacies association C (Fig. 8)

This lithofacies association consists of alternation of graptolitic shale, thin-bedded lime mudstone, and thin packstone lithofacies with Bouma division Tb or Tc (Figs. 4-C, D). Carbonate turbidites are generally 10-30 percent in thickness in the lithofacies. Lime mudstone is rather rare.

This association may be deposited in a basin plain near the slope, where it is occasionally affected by turbidity currents. Its modern analogues are the basinal, fine-grained sediments in the Bahamas, with 35 percent 'distal' turbidites (Tb-c or Tc) (Mullins and Neumann, 1979).

Lithofacies association D (Fig. 8)

This lithofacies association is dominated by graptolitic shale and lime mudstone lithofacies. Carbonate packstone, if it occurs, is generally thin-bedded, finer grained, and base-cut-out (e.g., Tc).

The characteristics of this lithofacies association are similar to those of lithofacies association C, but with a rather small percentage of turbidites, indicating that the depositional environment is far from the deposition of gravity-flow sediments. This association is representative of deposits in a basin plain.

Lithofacies sequences

Though debrites and turbidites have long been regarded as event deposits, the vertical succession of lithofacies and their associations in the Pingliang Formation shows regular changes in vertical transitions from one lithofacies association to another. Lithofacies sequences in the Pingliang Formation show two hierarchies: short-term and long-term lithofacies sequences.

Short-term lithofacies sequences

Two types of short-term lithofacies sequences have been distinguished in the Pingliang Formation: fining-upward and coarsening-upward lithofacies sequences. Fig. 7 shows legends for lithofacies, sedimentary structures and depositional settings in this paper. The Pingliang Formation is different from commonly described coarsening-upward cycles in deep water deposits (e.g., Yose and Heller, 1989; Masetti et al., 1991), as it is dominated by fining-upward successions, with a few showing coarsening-then-fining-upward trends. In addition, four shallowing-upward cycles were also distinguished in the lowermost part of the Pingliang Formation. These shallowing-upward cycles consist of lower, nodular argillaceous lime mudstone and upper, bioturbated lime mudstone; these are different from the short-term lithofacies sequences in the

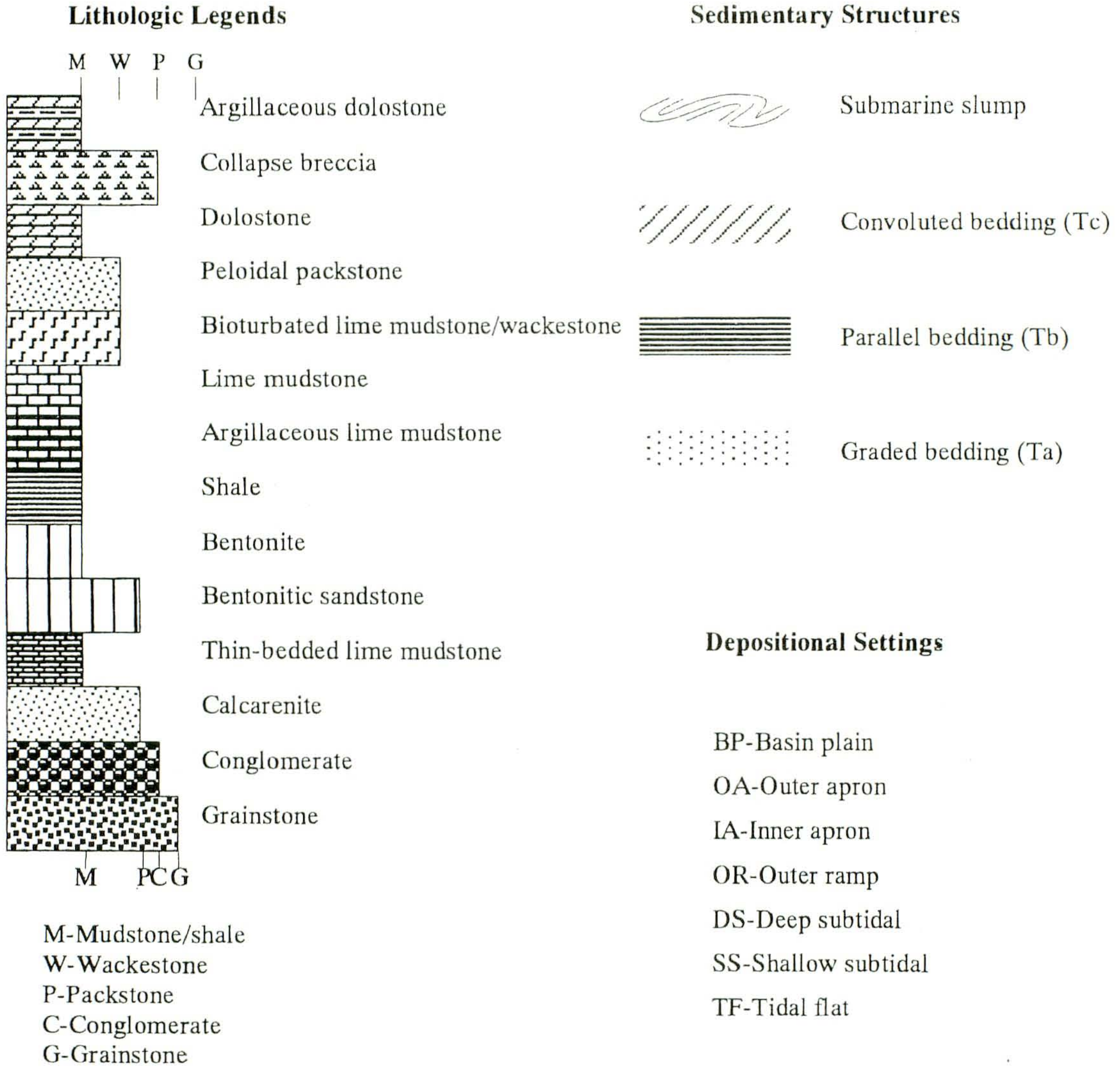

Fig. 7. Key to sedimentary log in following figures.

Pingliang Formation.

Twenty-one fining-upward lithofacies sequences have been distinguished in the Pingliang Formation in Pingliang. The fining-upward lithofacies sequences (Fig. 8-A) in the formation range from several meters to ten meters in thickness. The sequences commonly consist of, in ascending order, debrite-rich lithofacies (A), carbonate turbidites (B), alternation of carbonate turbidites and shales (C), and shale-rich lithofacies (D). Within such a sequence (Fig. 8-A), fine-grained sediments (e.g., shale, lime mudstone) increase upward, and bedding thickness decreases upward. Depositional processes of the sequence may have changed from debris flow to turbidity current and finally were dominated by vertical settling of fine-grained sediments. Thus, a fining-upward lithofacies sequence represents a retrograding deposition from inner apron to basin plain. Though some fining-upward sequences in the Pingliang Formation do not include all four lithofacies associations, they all show the depositional process in the preferred order (e.g., A→B→C→D, A→B→C, B→C→D, C→D).

Only five coarsening-upward lithofacies sequences were distinguished in the Pingliang Formation. The coarsening-upward succession (Fig. 8-B) consists of lower shale-dominant lithofacies (D), which grades upward into lithofacies association C, and then into turbidite-dominated lithofacies association B. Carbonate conglomerates (lithofacies association A) may sometimes cap the sequence. A coarsening-upward lithofacies sequence represents a prograding deposition from basin plain to inner apron settings.

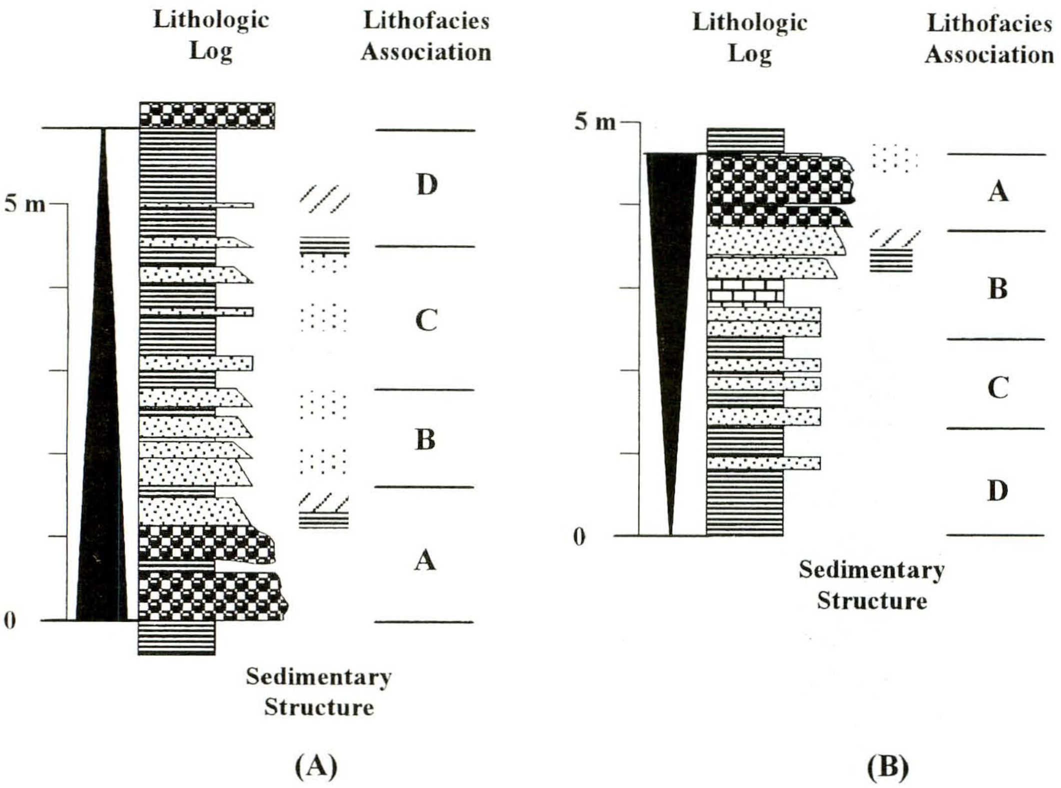

Fig. 8. Vertical successions of lithofacies associations in the Pingliang Formation. A-fining-upward succession; B-coarsening-upward succession and overlying fining-upward succession.

Long-term lithofacies sequence

In the Pingliang Formation, the short-term lithofacies sequences are further superimposed on six, long-term lithofacies sequences, as indicated by the stacking patterns of the short-term ones. One of the long-term lithofacies sequences in the Pingliang Formation is shown in detail in Fig. 9. This long-term sequence is composed of five short-term lithofacies sequences, which are arranged in retrograding order. The lowermost short-term cycle consists of carbonate grainstone/packstone and minor shale. The succeeding cycle is characterized by carbonate turbidites and interbedded shale. The overlying cycle shows clear grading from lower carbonate turbidites up to upper shales. The uppermost two short-term cycles, however, are dominated by shales deposited in basin plain settings. In short, this long-term lithofacies sequence is an asymmetric, fining-upward (retrograding) cycle, which is superimposed by 5 short-term cycles.

The Pingliang Formation, as a whole, is composed of 23 short-term lithofacies sequences, which are superimposed on 6 long-term lithofacies sequences (5 retrograding cycles plus 1 prograding cycle) (Fig. 10). The sedimentology of the Pingliang Formation at Pingliang is described below in the order of 6 long-term lithofacies sequences from bottom to top, namely Phase 1 to Phase 6.

Phase 1

This phase contains the lowest sediments of the Pingliang Formation exposed at the Sandaogou section (Fig. 2). The succession consists of the lower, outer ramp carbonates (nodular argillaceous lime mudstone, thin-bedded bioturbated lime mudstone, etc.) and upper, gravity-flow sediments, deposited on the inner apron. The boundary of this phase and the underlying Sandaogou Formation (Llanvirnian, Lower Ordovician) is a drowning unconformity in terms of Schlager and Camber (1986) and Schlager (1989), which is marked by the appearance of a vast amount of nodular argillaceous lime mudstone. The coeval boundary can be distinguished from other sections along the western and southern margins of the Sino-Korean Massif, suggesting that tectonic activity or sea level changes controlled the development of the boundary. The top of this phase is composed of shale and nodular argillaceous lime

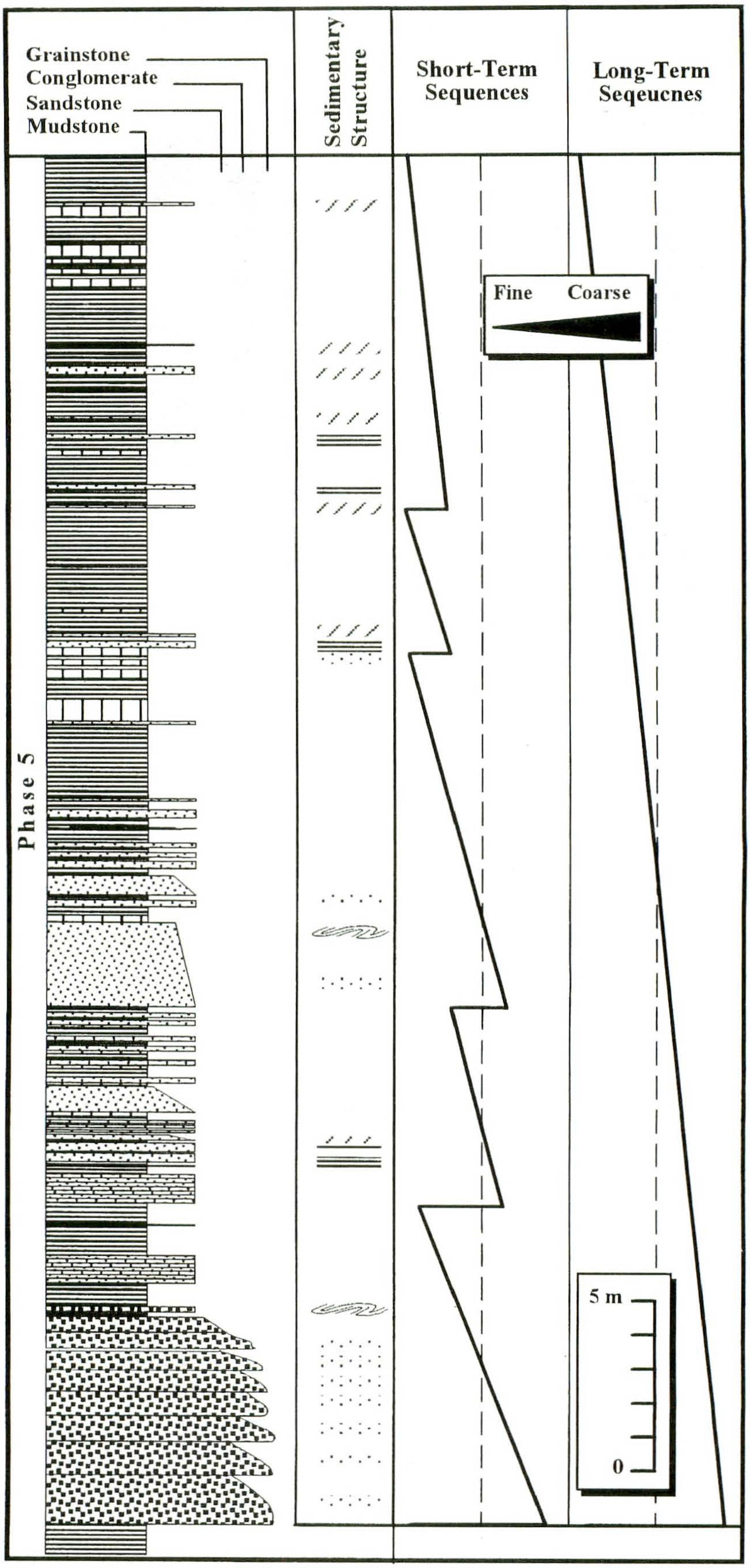

Fig. 9. Log of lithofacies selected from Phase 5 of the Pingliang Formation to show short-term lithofacies sequences superimposed on a long-term lithofacies sequence.

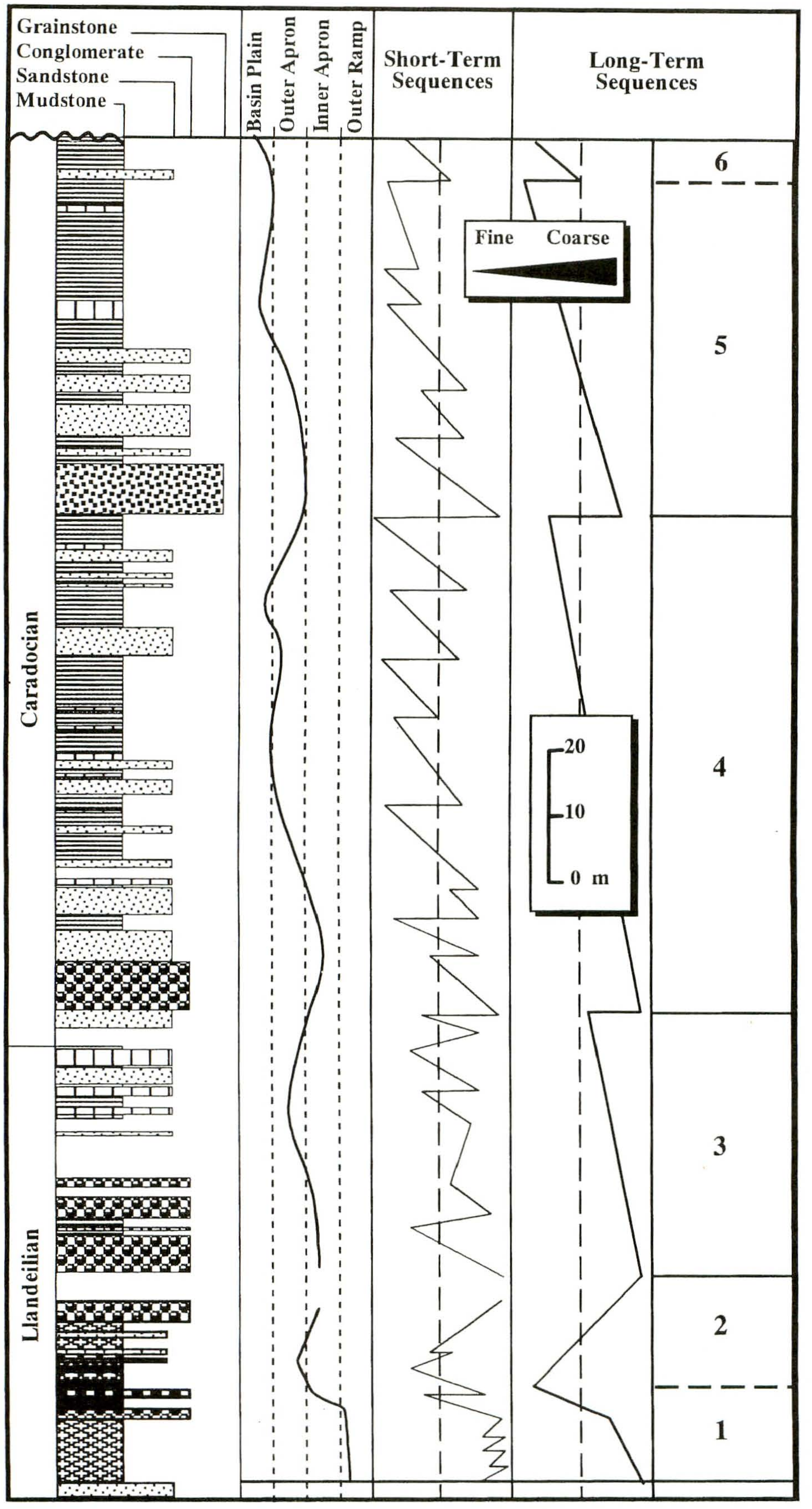

Fig. 10. Short-term lithofacies sequences superimposed on six, long-term lithofacies sequences in the Pingliang Formation in Pingliang.

mudstone deposited on the base of the basin plain. Phase 1, if described strictly, is a deepening-upward sequence, instead of a fining-upward one (Fig. 10).

Phase 2

This phase is the only prograding cycle in the Pingliang Formation. The lower boundary, with Phase 1 is ambiguous, and the upper boundary is not clear because of the covering of the exposure. The lower terrigenous muds are replaced by thin-bedded carbonate turbidites (lithofacies B). The cap of this phase is dominated by carbonate conglomerates, regarded as debrites (lithofacies A) (Fig. 10).

Phase 3

Within this part of the sequence, detailed depositional changes are not clear, due to part of the section being unexposed. The deposition of Phase 3 generally consists of lower, conglomerate-dominated lithofacies and overlying turbidites, characterized by packstone/volcanic sandstone (Fig. 10). Thus, this phase was deposited during a retrograding cycle.

Phase 4

This period began with about 6 m thick carbonate conglomerates, replaced by an overlying packstone-dominated lithofacies association. From here to the top of the phase, packstone decrease generally, and shale becomes the dominant component of deposition (Fig. 10). This is also a retrograding sequence.

Phase 5

During this period, the grainstone lithofacies at the bottom was replaced by carbonate packstone lithofacies with interbedded shale. The deposition of turbidites further decreased upward, and shale comprises most of the upper part of the interval (Fig. 10). This phase is also a retrogressive deposition, from outer apron to a basin-plain environment.

Phase 6

This phase marks the end of the deposition of the Pingliang Formation at Pingliang, though it is obvious that still younger strata might have been deposited but removed by later erosion. The deposition of this phase began with lithofacies C, which grades upward into terrigenous muds lithofacies (Fig. 10).

Controlling factors for lithofacies sequences

As described above, the Pingliang Formation is dominated by fining-upward lithofacies sequences of two orders. In other words, the deposition of the formation can also be described as fluctuation of frequency of gravity-flow sediment via defaulted fine-grained sediments. However, the mechanism controlling the deposition of gravity-flow carbonates is still a topic of debate.

Yose and Heller (1989) suggested that cyclic deposition of the basin-margin sequence could be affected by progradation/aggradation and collapse of the adjacent ramp/slope system. Autocyclic mechanism can explain the coarsening-upward cycles capped by large-scale collapse, but it cannot explain the deposition of fining-upward sequences dominating in the Pingliang Formation. Autocyclic collapse of slope sediments, if it exits, is difficult to explain how the clasts in the conglomerates of the Pingliang Formation came from different stratigraphic horizons. Moreover, if the lithofacies sequences were really controlled by autocyclic mechanisms, a random distribution of gravity-flow sediments would be expected. Such lithofacies sequences, as a result, should not be correlated basinally and intrabasinally.

We employed coeval strata of the Pingliang Formation on a shallow-water carbonate platform to verify whether development of deposition in deep water and shallow-marine environments could be reconciled. The Middle Ordovician shallow-marine carbonates in eastern North China, namely the Fengfeng Formation, are approximately coeval strata with the Pingliang Formation, based on the conodont studies (Table 2).

The Fengfeng Formation at Fengfeng of Hebei Province, eastern North China (based on field work by Liu, An, and Zhang, 1994, unpublished data) consists of two members (Table 2). The lower, Gezhuang Member, is characterized by solution collapse breccia and argillaceous dolostone, deposited on a supertidal flat. The upper, Badou Member, is dominated by subtidal as well as minor peritidal sediments (Fig. 11).

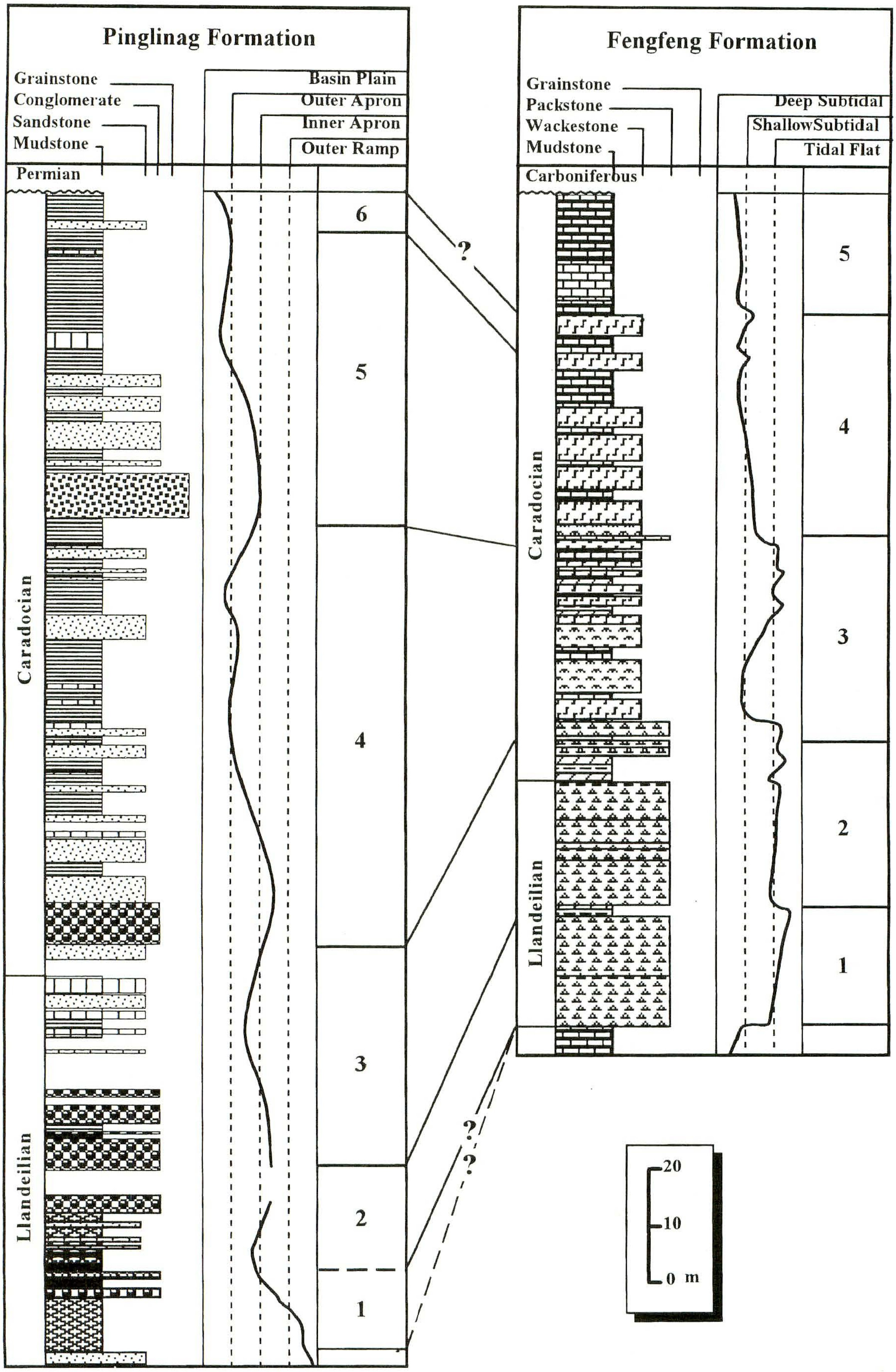

Fig. 11. Cyclic correlation between the long-term lithofacies sequences in the Pingliang Formation and the long-term shallowing-upward cycles in the Fengfeng Formation.

Hence, the Fengfeng Formation represents a retrograding deposition, which is similar to the general fining-upward trend of deposition of the Pingliang Formation. Moreover, the debrites in the lower Pingliang Formation were deposited during fall of sea level, and therefore can be correlated with lowstands sediments in the Fengfeng Formation.

On a more detailed level, the long-term lithofacies sequences in the Pingliang Formation can be correlated with long-term, shallowing-upward cycles (4th-order cycles ?) in the Fengfeng Formation (Fig. 11). Two argillaceous dolostone-capped cycles in the Gezhuang Member are correlatable with Phase 2 and Phase 3 (conglomerate-dominated, fining-upward lithofacies sequences) in the lower part of the Pingliang Formation, respectively. The overlying long-term cycle in the Badou Member, capped by solution collapse breccia, may be contemporaneous with Phase 4 (Fig. 11). The succeeding cycles in the Fengfeng Formation are dominated by subtidal, bioturbated lime mudstone and thin-bedded lime mudstone, showing similar stacking patterns with their coeval lithofacies sequences (Phase 5 and Phase 6) in the Pingliang Formation (Fig. 11). The uppermost, long-term sequence in the Fengfeng Formation, may be younger than the Pingliang Formation.

Hence, deposition of long-term lithofacies sequences in the Pingliang Formation was not the result of autocyclic collapse of sediments on a carbonate platform and slope after progradation, or accompanying local tectonic events. Instead, sea-level fluctuations have been the primary cause of the sedimentation patterns of the Pingliang Formation in Pingliang. However, it is not clear whether the short-term lithofacies sequences in the Pingliang Formation can be correlated with meter-scale cycles in shallow-marine carbonates without further detailed work.

The drowning unconformity and overlying lithofacies sequences in the Pingliang Formation show controversial sea-level fluctuation, compared with the lowermost part of the Fengfeng Formation (Fig. 11). We suggest that the lower unconformity of the Pingliang Formation might have been controlled mainly by a tectonic event, especially affecting the deposition along the south margin of the Sino-Korean Massif.

Summary

The Middle Ordovician Pingliang Formation in Pingliang consists of a large amount of gravity-flow sediments and fine-grained sediments (shale and lime mudstone). Various lithofacies in the formation can be grouped into five lithofacies associations, deposited on the outer ramp, apron, and basin plain environments.

Short-term fining-upward and coarsening-upward lithofacies sequences have been distinguished from the studied strata. The fining-upward lithofacies sequences consist, generally, of coarse, thick debrites and/or turbidites which grade upward into fine-grained sediments. The coarsening-upward lithofacies sequences consist of lower, fine-grained deposits to upper turbidite/debrite-dominated lithofacies. The short-term lithofacies sequences in the formation are superimposed on six long-term successions. The vertical succession of the lithofacies shows further that the Pingliang Formation was deposited as a long-term retrogradation from outer apron to basin plain environments.

The deposition of the Pingliang Formation shows synchronous changes with that of the coeval Fengfeng Formation was deposited on the shallow-marine carbonate platform of North China. Debrite-rich intervals in the lower part of the Pingliang Formation can be correlated with lowstands deposits, characterized by solution collapse breccia/argillaceous dolostone of the Fengfeng Formation, suggesting that the former might also have been deposited mainly during lowstands of sea level. By contrast, terrigenous, mud-dominated sedimentation in the basin took place during sea-level highstands. The long-term lithofacies sequences in the Pingliang Formation can be correlated with long-term, shallowing-upward cycles in the Fengfeng Formation.

This study indicates that development of gravity-flow deposits in the Pingliang Formation in Pingliang was largely controlled by sea-level fluctuation rather than by autocyclic factors or local tectonic activity.

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References

Aigner, D.K., 1985, Storm depositional systems: dynamic stratigraphy in modern and ancient shallow-marine sequences. *Lecture Notes in Earth Science*, no. **3**, Berlin, Springer-Verlag, 174 p.

An, T., 1986, Recent process in Ordovician System of North China Stratigraphical Province. In: *Selected Paper from Department of Geology, Peking University (1984)*, Geological Publishing House, 44-58. (in Chinese with English abstract)

An, T., and Zheng, Z., 1990, *The Conodonts of the Marginal Areas Around the Ordos Basin, North China*. Science Press. 201 p. (in Chinese with English abstract)

Bergström, S.M., 1977, Early Paleozoic biostratigraphy in the Atlantic Borderland. In: Swain, G.M., (ed.), *Stratigraphic Micropaleontology of Atlantic Basin and Borderlands*. Elsevier Science Publishing Company, Amsterdam, 85-110.

Chen, J., Zhou, Z., Lin, Y., Yang, X., Zou, X., Wang, Z., Lou, K., Yao, B., and Shen, H., 1984, Ordovician Biostratigraphy of Western Ordos. *Memoirs of Nanjing Institute of Geology and Palaeontology, Academia Sinica*, no. **20**. 1-31. (in Chinese with English abstract)

Coniglio, M.C., and Dix, G.R., 1992, Carbonate slopes. In: Walker, R.G., and James, N.P., (eds.), *Facies Models: Response to sea level change*. 349-373.

Cook, H.E., 1983, Ancient carbonate platform margins, slopes and basins. In: Cook, H.E., Hine, A.C., and Mullins, H.T., (eds.), *Platform Margin and Deep Water Carbonates*. Society of Economic Paleontologists and Mineralogists, Short Course **12**, 1-189.

Cook, H.E., and Mullins, H.F., 1983, Basin margin environments. In: Scholle, P.A., Bebout, D.E., and Moore, C.H., (eds.), *Carbonate Depositional Environments*. American Association of Petroleum Geologists Memoir **33**, 539-617.

Cook, H.E., and Taylor, M.E., 1991, Carbonate-slope failures as indicators of sea-level lowerings. *American Association of Petroleum Geologists Bulletin*, **75**, 556.

Crevello, P.D., and Schlager, W., 1980, Carbonate debris sheets and turbidites, Exuma Sound, Bahamas. *Journal of Sedimentary Petrology*, **50**, 1121-1148.

Dromart, G., Ferry, S., and Atrops, F., 1993, Allochthonous deep-water carbonates and relative sea-level changes: the Upper Jurassic-Lowermost Cretaceous of southeast France. In: Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., (eds.), *Sequence Stratigraphy and Facies Associations*. Special Publication of the International Association of Sedimentologists **18**, 295-305.

Droxler, A.W., and Schlager, W., 1985, Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas. *Geology*, **13**, 799-802.

Enos, P., and Moore, C.H., 1983, Fore-reef slope environments. In: Scholle, P.A., Bebout, D.G., and Moore, C.H., (eds.), *Carbonate depositional environments*. American Association of Petroleum Geologists Memoir **33**, 508-537.

Fortey, R.A., Harper, D.A.T., Ingham, J.K., Owen, A.W., and Rushton, A.W.A., 1995, A revision of Ordovician series and stages from the historical type area. *Geological Magazine*, **132**, 15-30.

Gawthorpe, R.L., 1986, Sedimentation during carbonate ramp-to-slope evolution in a tectonically active area: Bowland Basin (Dinantian), North England. *Sedimentology*, **33**, 185-206.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1989, *A Geologic Time Scale*. New York, Cambridge University Press, 128 p.

Lindström, M., 1971, Lower Ordovician succession of conodont fauna. *Report International Geological Congress, 21st*, **7**, 88-96.

Liu, J., An, T., and Zheng, Z., 1996, Sedimentary evolution of the Ordovician Basin in central

Ningxia, North China. *Journal of Geosciences, Osaka City University*, **39**, 83-110.

Masetti, D., Neri, C., and Bosellini, A., 1991, Deep-water asymmetric cycles and progradation of carbonate platforms governed by high-frequency eustatic oscillations (Triassic of the Dolomites, Italy). *Geology*, **19**, 336-339.

McIlreath, I.A., and James, N.P., 1984, Carbonate slopes. In: Walker, R.G., (ed.), *Facies Models*. Geoscience Canada Reprint Series **1**, 245-257.

Mullins, H.J., 1983, Comments and reply on "eustatic control of turbidites and winnowed turbidites". *Geology*, **11**,.57-58.

Mullins, H.J., and Cook, H.E., 1986, Carbonate apron models: alternatives to the submarine fan model for paleoenvironmental analysis and hydrocarbon exploration. *Sedimentary Geology*, **48**, 37-79.

Mullins, H.J., and Neumann, A.C., 1979, Deep carbonate bank margin structure and sedimentation in the northern Bahamas. In: Doyle, L.J., and Pilkey, O.H., (eds.), *Geology of Continental Slopes*. Society of Economic Paleontologists and Mineralogists, Special Publication **27**, 165-192.

Mullins, H.J., Neumann, A.C., Wilber, R.J., Hine, A.C., and Chinburg, S.J., 1980, Carbonate sediment drifts in the northern straits of Florida. *American Association of Petroleum Geologists Bulletin*, **64**, 1701-1717.

Reading, H.G., and Levell, B.K., 1996, Controls on the sedimentary rock record. In: Reading, H.G., (ed.), *Sedimentary Environments: Processes, Facies and Stratigraphy* (3rd edition). Blackwell Science, 5-36.

Ross, R.J., James, N.P., Hintze, L.F., and Poole, F.G., 1989, Architecture and evolution of a Whiterockian (early Middle Ordovician) carbonate platform, Basin Ranges of western U.S.A. In: Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F., (eds.), *Controls on Carbonate Platform and Basin Developments*. Society Economic Paleontologists and Mineralogists Special Publication **44**, 167-184.

Sarg, J.F., 1988, Carbonate sequence stratigraphy. In: Wigus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., and Van Wagoner, J.C., (eds.), *Sea Level Changes: An Integrated Approach*. SEPM Special Publication **43**, 155-181.

Schlager, W., 1989, Drowning unconformities on carbonate platforms. In: Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F., (eds.), *Controls on Carbonate Platform and Basin Developments*. Society Economic Paleontologists and Mineralogists Special Publication **44**, 15-25.

Schlager, W., and Camber, O., 1986, Submarine slope angles, drowning unconformities, and self-erosion of limestone escarpments. *Geology*, **14**, 762-765.

Schlager, W., Rijmer, J.J.G., and Droxler, A., 1994, Highstand shedding of carbonate platforms. *Journal of Sedimentary Research*, **B64**, 270-281.

Shanmugam, G., and Moiola, R.J., 1984, Eustatic control of calciclastic turbidites. *Marine Geology*, **56**, 273-278.

Wanlass, H.R., 1979, Limestone response to stress: pressure solution and dolomitization. *Journal of Sedimentary Petrology*, **49**, 437-462.

Williams, A., Strachan, I., Bassett, D.A., Dean, W.T., Ingham, J.K., Wright, A.D., and Whittington, H.B., 1972, A Correlation of the Ordovician Rocks in the British Isles. *Geological Society of London Special Report*, no. **3**, 74 p.

Wilson, J.E., 1975, *Carbonate facies in geologic history*. Springer-Verlag, New York, 471 p.

Yose, L.A., and Heller, P.L., 1989, Sea-level control of mixed-carbonate-siliciclastic, gravity-flow deposition: Lower part of the Keeler Canyon Formation (Pennsylvanian), southeastern California. *Geological Society of America Bulletin*, **101**, 427-439.